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RESEARCH MEMORANDUM

FACTORS CONTROLLING AIR-INLET FLOW DISTORTIONS

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NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS

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SUMMARY

A study of several typical air induction systems for modern aircraft indicate that flow distortions of about-pipe-flow magnitudes can be expected at near-optimum inlet-engine matched air-flow conditions and at small angles of attacks. These distortions may be seriously increased by operation at large angles of attack or yaw, or by supercritical operation of the inlets.

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Boundary-layer bleed, duct overexpansion and contraction, and freely rotating fans appear promising as devices for reducing distortions with little cost in propulsive thrust. Duct lengthening is also an effective device if the distortions are greater-than-pipe-flow magnitude, as they usually are during angle of attack or yaw operation. Duct lengthening, however, can not reduce distortions below the pipe-flow values. If screens are used, they should be installed in a region of low duct Mach number if large pressure losses are to be avoided.

INTRODUCTION

Flow distortions at the face of highly loaded axial compressors have to a serious degree adversely affected the performance of some turbojet engines. For one thing, flow distortions cause surge to occur earlier, thereby reducing engine acceleration margins and altitude operating limits. In addition, local increases in turbine gas temperature may occur, requiring an engine thrust derating as a protective measure. Other undesirable phenomena such as rotating stall, increased compressor-blade vibratory stresses, and reduced engine mass flows may also be present.

As an example of the quantitative effects of a flow distortion, recently published data indicate that on the average a 2-percent increase in distortion requires a 1-percent decrease in engine thrust rating.

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Turbojet engines vary substantially in their toleration of a flow distortion. Some engines are more affected by radial distortions, while other engines are more affected by circumferential distortions. Because air-induction systems feed the turbojet engine with flow distorted both radially and circumferentially, both kinds of engines can experience serious operational difficulties.

SYMBOLS

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D	inlet throat hydraulic diameter
h/δ	ratio of fuselage diverter height to boundary-layer thickness
L	diffuser duct length
M_0	flight Mach number
P	total pressure
V	velocity
$\frac{W\sqrt{\theta}}{\delta A}$	corrected weight-flow, lb/(sec)(sq ft)

Subscripts:

av	average
max	maximum
min	minimum

DISCUSSION OF INLET DISTORTION

The magnitude of flow distortions in the ducts of modern aircraft at engine-inlet matched air-flow conditions is shown in figure 1 as a function of free-stream or flight Mach number. The data are presented for cruise angles of attack varying from 0° to $3\frac{1}{2}^\circ$, depending on the airplane.

The flow distortion parameter combines both radial and circumferential distortions. It is defined as the difference between the maximum and minimum total pressure existing over the compressor-face flow area to within about 95 percent of the duct radius divided by the average total pressure. Inlet geometries (fig. 2) represented include a variable-wedge inlet, fixed half-cone inlets, a translating-cone nacelle inlet, variable-ramp twin inlets, fixed-scoop twin inlets, and a fixed-ramp inlet mounted beneath a research-model fuselage.

Wide variations in distortion with flight Mach number and inlet design are obvious from these data. As a group, the distortions vary from 9 to 23 percent at a Mach number of about 0.6 to from 7 to 12 percent at a Mach number of 2.0. Furthermore, some inlet designs appear to have a wide variation in distortion with Mach number, whereas others have little variation with Mach number. For example, airplane A has a distortion of 23 percent at Mach number 0.6 and 7 percent at Mach number 2.0, compared with a nearly constant 12-percent distortion over the same Mach number range for airplane B.

An explanation of this difference can be made with the aid of figure 3, where the effect of duct discharge flow rate on flow distortion is presented. The same distortion data appearing in figure 1 are shown here. For any inlet, distortion is a primary function of the air flow rate. Furthermore, the experimental trends parallel the variation in distortion of a turbulent-pipe-flow profile calculated to within 95 percent of the duct radius. Of course, it should not be inferred from these data that inlet flow distortions will always follow the pipe-flow curve; however, it is a convenient reference distortion that can be used particularly in evaluating the effectiveness of distortion-reduction devices.

Now, it may be surprising to see a variation in distortion for pipe flow, but this variation in total-pressure distortion is a natural consequence of a fixed velocity profile. To digress for a moment, the relation between pipe-flow velocity profile and pipe-flow total-pressure profiles is shown in figure 4. A turbulent-pipe-flow velocity profile is plotted, and this profile is ideally independent of flow rate. The velocity distortion calculated from the center of the duct to 95 percent of the duct radius is a constant of 42.8 percent for any flow rate.

When a total-pressure profile is calculated from this velocity profile, a steep profile having 19.0-percent distortion is obtained for a high flow rate of 40 pounds per second per square foot, whereas a flat profile having 3.8-percent distortion is obtained for a low flow rate of 20 pounds per second per square foot. Although the magnitudes of the experimental distortions shown in figure 3 are about the same as pipe-flow distortions, the profiles, of course, can be quite different from those shown in figure 4.

Returning now to the differences in the variation of distortion with flight Mach number of airplanes A and B, the air flow captured by the variable inlet of airplane A varied from 27 pounds per second per square foot at a Mach number of 2.0 to 41 pounds per second per square foot at a Mach number of 0.6. The air flow captured by the fixed inlets of airplane B, on the other hand, varied only from 28.8 to 31.5 pounds per second per square foot over the flight Mach number range of 2.0 to 0.8.

The differences in distortion with Mach number arises from a difference in the engine-inlet air-flow matching technique. Both airplanes have engines requiring a great variation in air flow with flight Mach number. The inlet on airplane A follows the engine air-flow require- 4042
ment and delivers this great variation in air flow directly to the compressor inlet. Thus a great change in distortion with flight Mach number occurred. The inlets of airplane B, however, deliver a nearly constant air flow at the duct discharge that is greater than the engine requirements. The excess weight flow (up to 34 percent) is then bypassed ahead of the compressor inlet. Little distortion variation with Mach number resulted.

The discussion has thus far been concerned with well-designed inlets employing advanced techniques for high levels of performance. Furthermore, the data have been restricted to near-optimum performance, matched air-flow conditions, and low angles of attack. However, the pattern and magnitude of flow distortion vary substantially with conditions of inlet operation and with angles of attack or yaw.

The effect of both subcritical and supercritical operation on distortion is shown in figure 5. Distortion is plotted as a function of air-flow rate. Data are presented for airplane E at a flight Mach number of 0.9 and for the research model at Mach number 2.0. In the subcritical range both induction systems follow the pipe-flow curve very closely until near-critical-flow conditions are approached. Near critical flow, the distortions gradually diverge from the pipe-flow curve and become sharply adverse as increasing supercritical operation is permitted. The sharp increase in distortion with supercritical operation probably arises from duct flow separations caused by internal-shock - boundary-layer interaction.

The effect of yaw angle on the flow distortions of airplanes A and D is shown in figure 6 at different Mach numbers at matched air-flow conditions. When an airplane is yawed or pitched, the air inlet experiences nonuniform flow compression or even local flow separations not encountered at the cruise attitude. These conditions cause an increase in flow distortion at the air-inlet entrance that are carried back to the compressor-face station. These data show that increasing the yaw angle increases the distortion. An average of these data indicates that about a $1\frac{1}{2}$-percent increase in distortion can be expected for each 2° increase in yaw up to 6°. Although the inlet geometries and locations are quite different, there is no significant difference between the airplanes as to the effect of yaw on flow distortion.

The effect of angle of attack on the flow distortions of a conical spike nacelle inlet is shown in figure 7. These data were obtained with a research model at a free-stream Mach number of 2.0 for a fixed air-flow rate at a subcritical mass-flow ratio. Distortions were measured at four stations along the diffuser. Duct stations are located in terms of inlet hydraulic diameters from the cowl lip. A marked increase in distortion at all stations was obtained with increases in angle of attack, the sharpest increase occurring near the inlet throat region. The distortion rapidly decreased through the diffuser as a result of both mixing induced by viscous shear forces and reduced duct Mach number. However, a sizeable distortion at the compressor-face station still existed, being 18 percent at 8° angle of attack compared with 7 percent at zero angle of attack.

Centerbody bleed shown in the sketch of figure 7 of about 6 percent of the duct flow did not alter this condition. This might be expected since, although the bleed system removed the separated flow from the centerbody, shock-induced separation on the internal wall of the cowl was not removed.

METHODS OF REDUCING DISTORTION

To this point it has been shown that carefully designed air-induction systems at matched air-flow conditions have distortions of a magnitude about that of turbulent pipe flow. Furthermore, it has been shown that internal duct flow separations that occur at some necessary airplane flight attitudes can markedly increase these distortions above the pipe flow magnitude. It is obvious, then, that some new methods in induction-system design are required to solve the problem. The remaining figures present data obtained at the NACA Lewis laboratory on some of the more promising methods investigated.

In figure 7, it was noted that inlet throat bleed was ineffective in reducing distortion, because a flow separation on the internal wall of the cowl was not removed. The reduction in distortion with inlet throat bleed for no flow separation on the internal wall of the cowl is shown in figure 8, where distortion is plotted as a function of air-flow rate. Two bleed systems were used. One system is the conventional external boundary-layer diverter, which prevents fuselage boundary-layer air from entering the inlet. To determine the effects of allowing some fuselage boundary-layer air to enter the inlet, the compression ramp could be lowered into the boundary layer. The second system was used to remove any boundary-layer or flow separations on the ramp surface. This system consisted of a bleed slot spanning the width of the inlet and located on the ramp at the inlet throat.

With no throat bleed and with the inlet placed two-thirds into the fuselage boundary layer, which is an h/δ of $1/3$, distortions of 30 percent were obtained. As the inlet was raised out of the fuselage boundary layer, progressive improvements in flow distortion resulted. However, distortions much greater than pipe-flow values still persisted. This flow distortion resulted from the separation caused by the interaction of the terminal shock and the ramp-surface boundary layer.

When throat bleed was used to remove this flow separation, a reduction in distortion to near-pipe-flow values was obtained; and this improved distortion was obtained regardless of the amount of fuselage boundary-layer air entering the inlet. Furthermore, this reduction in distortion with throat bleed was accompanied by a 5-percent improvement in pressure recovery. 4042

Another suggested method of reducing distortion is that of lengthening the duct to provide increased mixing length. Figure 9 shows when duct lengthening will be effective. Distortion is plotted as a function of duct length in inlet hydraulic diameters. The data shown are for the air-induction systems of the aircraft presented in figure 1, with the addition of data for a research inlet where the effects of duct length were specifically studied. The air-flow rate was held constant at 30 pounds per second per square foot. For side-inlet configurations, where no internal bleed system was used to remove compression-surface flow separations, there is a marked reduction in distortion as the duct is lengthened. As the value of pipe-flow distortion, about 9 percent for all these data, is approached, further duct lengthening proves ineffective. When throat bleed is used to remove ramp surface flow separations, thereby reducing the distortion to pipe-flow value, again no effect of duct lengthening is noted. The same appears to be true for the nacelle cone inlet system.

The improvement in distortion obtained with a research model in which the duct was initially overexpanded and then contracted to the compressor-face station is presented in figure 10. Two principles are exploited by this method. By first overexpanding the duct, the distortion is reduced, as has already been discussed, by reducing the flow to a low Mach number or air-flow rate. In the second step, a principle used for years with wind tunnels, the distortions are further reduced by the strong mixing promoted by rapidly accelerating the flow to the compressor face.

The original diffuser had a distortion of from 4 to 6 percent over the compressor-face air-flow range. This distortion lies about 2 percent above the pipe-flow value. When the diffuser was modified to include a 25-percent-greater-flow-area section ahead of the compressor-face station, the distortion was reduced to about 1 to 2 percent. A 1-percent loss in pressure recovery was experienced in changing to the modified diffuser.

This is the one method studied thus far giving distortions below the pipe-flow value with little loss in total pressure.

Two forced-mixing devices are also being studied at this laboratory: (1) a freely rotating blade row or fan and (2) screens. Figure 11 shows the flow distortion in a duct with the fan as a function of the distortion existing without the fan. A freely rotating fan reduces distortion by transferring energy from regions of high velocity to regions of low velocity. The fan reduced a 10-percent distortion to 8 percent and a 30-percent distortion to 17 percent. Little difference was obtained between fans with 16 or 32 blades.

Pressure drops across the fan rotating in distorted flow have not been obtained as yet. However, pressure drops across the 16-blade fan of about 1 to 2 percent and across the 32-blade fan of about 2 to 3 percent have been measured in undistorted flow. These values represent minimum losses, of course, and may be somewhat higher in a distorted flow. These are results from the very first attempts of the laboratory to reduce flow distortions with fans and should not be considered as representative of the best that can be obtained. Research on this very promising device is continuing at the NACA Lewis laboratory.

Screens placed across the duct will reduce distortions, as noted on figure 12, where distortion is plotted as a function of screen solidity. The loss in pressure across a screen is seen to be a function of both screen solidity and duct Mach number. In reducing a 13-percent distortion to 6 percent, a 7-percent loss in pressure was incurred at a duct Mach number of 0.37 compared with a 1-percent loss in pressure at a duct Mach number of 0.2. Thus, if screens are to be used as a distortion-reduction device, they should be installed where low duct Mach numbers exist if large pressure losses are to be avoided. However, at very high flight Mach numbers, of the order of 3.5 to 4, screens may prove to be very attractive devices, because (1) a loss of 7 percent in total pressure is not the serious problem that it is in the low supersonic Mach number angle, and (2) screen icing will be nonexistant.

CONCLUDING REMARKS

In summary, research on modern air-induction systems indicates that flow distortions of about-pipe-flow magnitude can be expected at near-optimum inlet-engine matched air-flow conditions and cruise angles of attack, independent of flight Mach number. These distortions are seriously increased by allowing duct flow separation or nonuniform inlet flow as are encountered with poor inlet designs or with good inlet designs at angles of pitch or yaw.

Useful devices for reducing distortions at little cost in propulsive thrust include boundary-layer bleed, duct overexpansion and contraction, and freely rotating fans. Duct lengthening is also an effective device if distortions are greater than pipe-flow magnitude, but it is ineffective in reducing distortions below pipe-flow magnitude. If screens are used to reduce flow distortions, they should be installed where a low duct Mach number exists, if large pressure losses are to be avoided.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 23, 1956

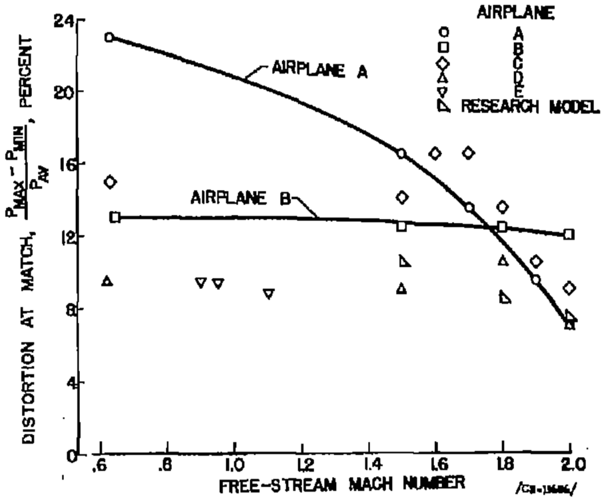


Figure 1. - Flow distortions in aircraft ducts at matched conditions. Cruise angle of attack.

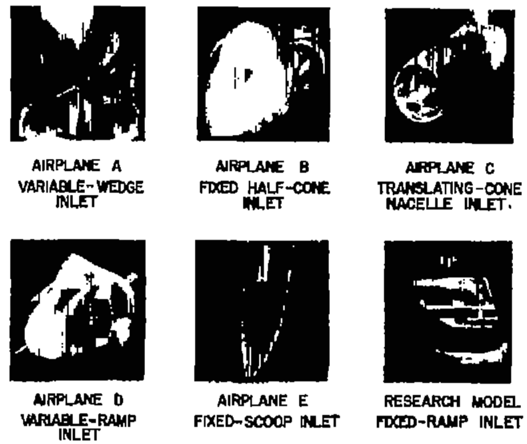


Figure 2. - Inlet geometries investigated.

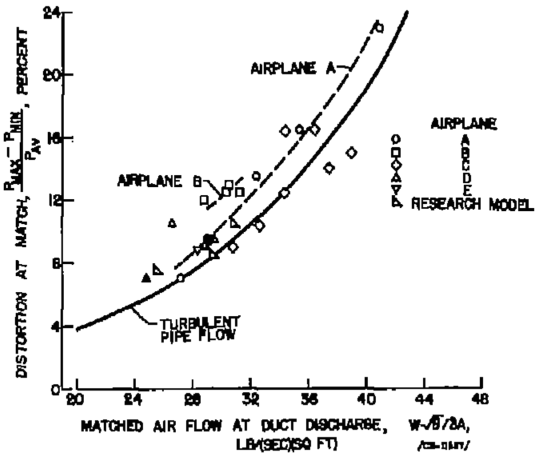
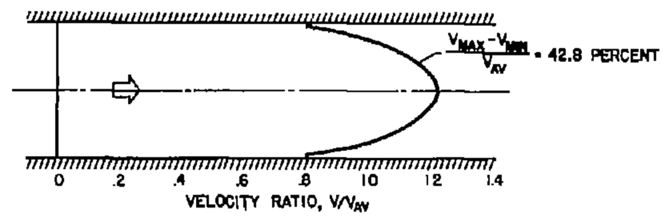
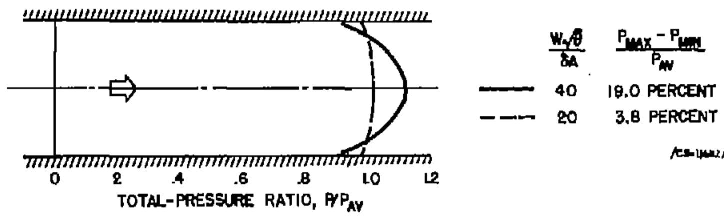


Figure 3. - Effect of duct discharge flow on flow distortion. Cruise angle of attack.



(a) Velocity profile for any flow rate.



(b) Total-pressure profiles for high and low flow rates.

Figure 4. - Pipe flow profiles.

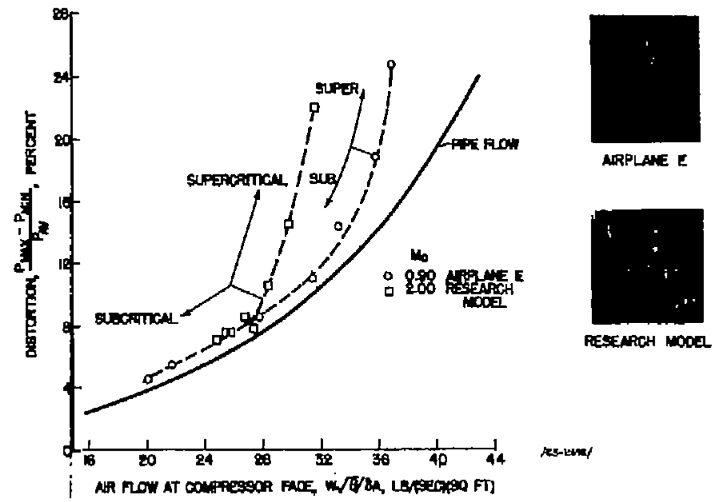


Figure 5. - Effect of supercritical and subcritical operation on flow distortion.

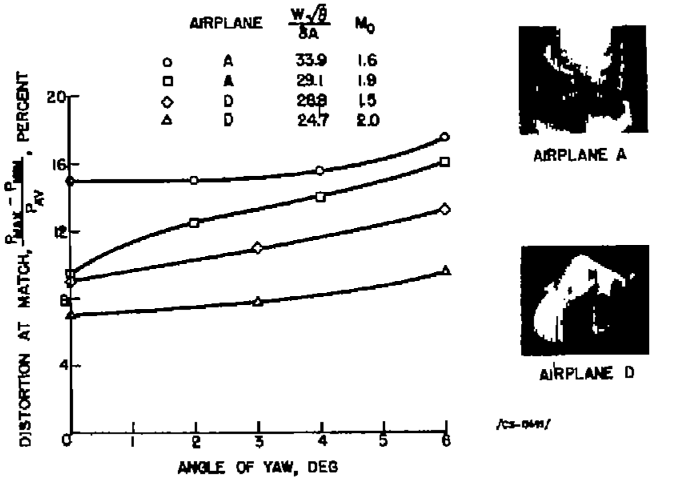


Figure 6. - Effect of yaw angle on flow distortion.

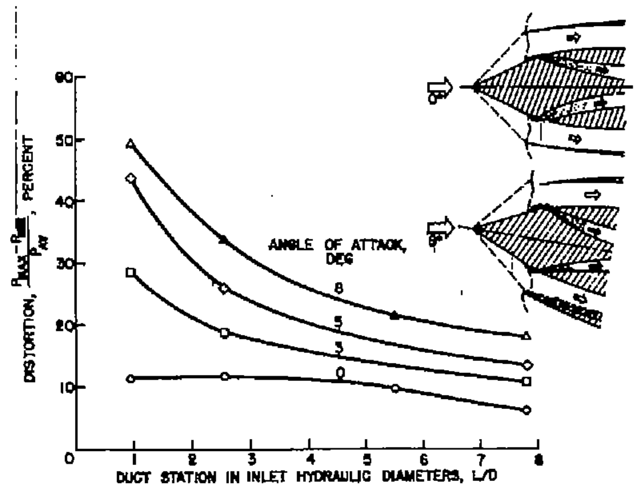


Figure 7. - Effect of angle of attack on flow distortion. Free-stream Mach number M_0, 2.0.

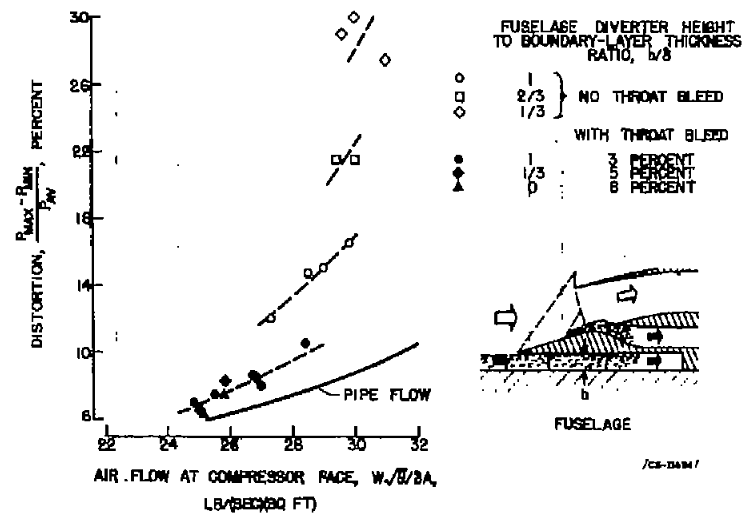
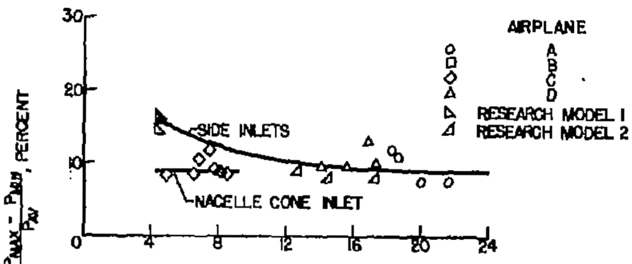
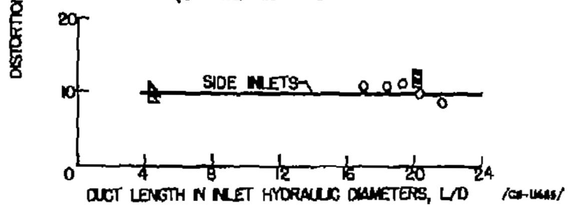


Figure 8. - Reduction of flow distortion with throat bleed. Free-stream Mach number M_0, 2.0.



(a) Without bleed.



(b) With bleed.

Figure 9. - Effect of duct length on flow distortion.

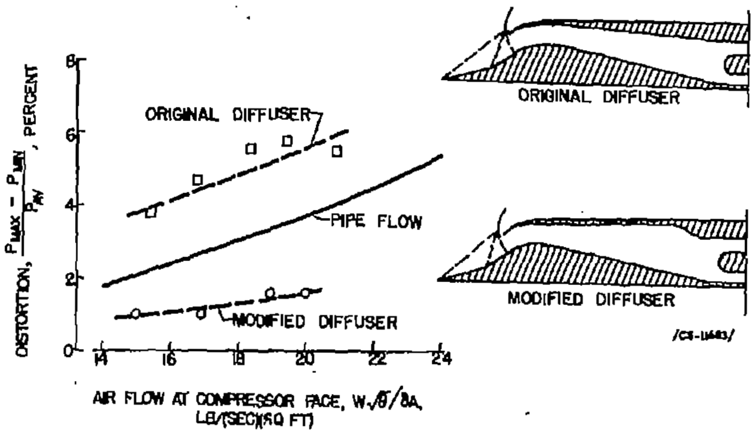


Figure 10. - Reduction of distortion by overexpanding and contracting the duct. Free-stream Mach number M_0, 3.07.

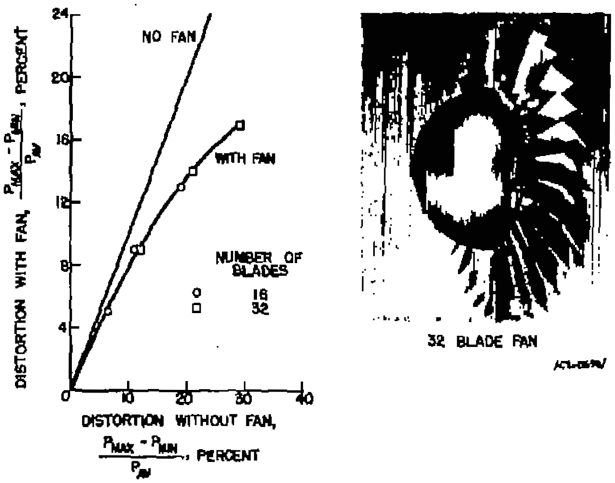


Figure 11. - Reduction of distortion with freely rotating fan.

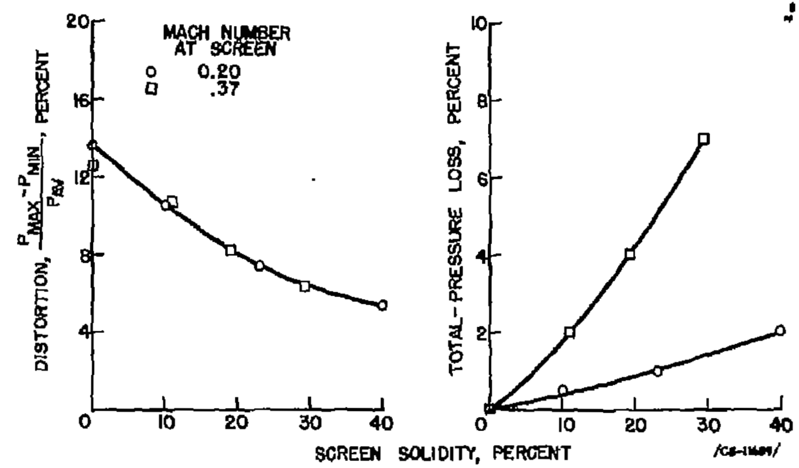


Figure 12. - Effect of screen solidity on flow distortion.